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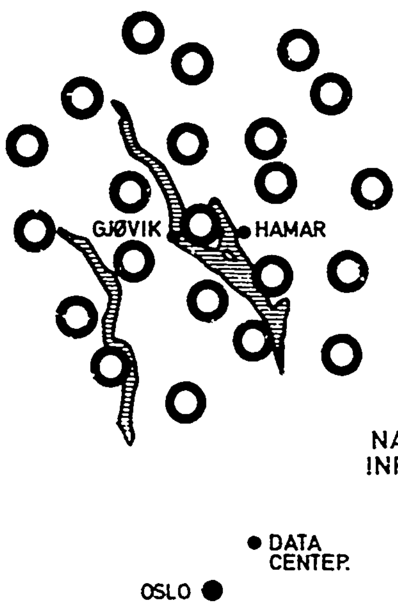

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NORWEGIAN SEISMIC ARRAY

NORSAR

P.O. Box 51. 2007 Kjeller-Norway

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13. ABSTRACT

This report covers the period 1 July 1970 - 30 June 1971 which is characterized by system developments and software debugging efforts, establishing of organizational procedures required for the routine NORSAR operation and research aimed at system improvements and array performance evaluation. The most important single event in the reporting period was that the NORSAR array became operational in March 1971. ( )

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NORSAR RESEARCH AND DEVELOPMENT
1 July 1970 - 30 June 1971

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The NORSAR research project has been sponsored by the United States of America under the overall direction of the Advanced Research Projects Agency and the technical management of Electronic Systems Division, Air Force Systems Command, through Contract No. F19628-70-C-0283 with The Royal Norwegian Council for Scientific and Industrial Research.

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CONTENT

SUMMARY

This report covers the period 1 July 1970 - 30 June 1971 which is characterized by system developments and software debugging efforts, establishing of organizational procedures required for the routine NORSAR operation and research aimed at system improvements and array performance evaluation. The most important single event in the reporting period was that the NORSAR array became operational in March 1971.

In chapter II of the report which summarizes the joint efforts of the NTNF/NORSAR staff, development work and related topics are outlined. Emphasis is on the NORSAR software systems which main tasks are data recording on tape, event detection and routine analysis of recorded events. Research work completed and in progress is discussed in chapter III. The first 5 sections deal with typical NORSAR system subjects like time delay measurements, beam steering corrections and error location vectors, and filter setting for additional noise suppression during beamforming. The problem of defining a best-in-average event detection processor using real and simulated data, is discussed in section III, 6. Coherence and spectral analysis (section III, 7) are aimed on system improvements and also constitute a basis for array performance evaluation. A review of an investigation of the mantle structure is given in section III, 8. Appendix I and II give a preliminary set-up of the weekly bulletin and abstract of papers published in the reporting period.

I INTRODUCTION

This report covers the interval 1 July 1970 to 30 June 1971, a period which is characterized by the successful completion of field installations and software developments. The array became operational in March 1971, thus marking a new period in the NORSAR project.

Even after routine recordings and processing of NORSAR recorded signals started, large efforts were still invested in software developments as a sizeable group from IBM (Federal System Division) remained at NDPC, Kjeller. That contract is to terminate Aug 31, 1971.

The transformation of the NORSAR array into an operational seismological observatory has profoundly affected the research and system development work. As of today we are actually running the NORSAR array continuously, and this task in itself represents an additional workload on the research group. The system developments during the reporting period have been within the frame of the designed software system and naturally, in close cooperation with the IBM group. Moreover, the first and significant steps for analysis of long periodic data have been undertaken.

The research topics investigated or in progress, are oriented towards system operation and evaluation. The above subjects comprise travel time and wave velocity measurements and feed-back of this information into the system. Spectral analysis are used for estimating signal energy losses during routine processing, and gains in SNR as a function of different processing schemes. Several types of SNR measurements in the time domain have been performed and the VESPA analysing technique has been adapted to the NORSAR system. Most of the above analysis is tied to Plan D or interim NORSAR data which is based on recordings at a 10 Hz sampling rate from 18 seismometers in different subarrays. Also, long period waves from a few events in Asia have been analysed on an experimental basis.

II SYSTEM DEVELOPMENTS

Originally NORSAR was planned to be operational in 1969, then in summer 1970 and finally in winter 1970/71. As mentioned above, the array was completed in March 1971 when near continuous recording and routine processing of

incoming signals started. The above occasion represents a major event for those involved in the development of the NORSAR array, and naturally had a profound impact on the NDPC staff. What we have in mind here is that actual operation of a large and complex processing system which NORSAR represents, requires establishing a large number of daily working routines and procedures. (This involves first of all the reporting and eliminating bugs in the software system.) However, the real challenge is that the experience gained by operating NORSAR should put us in a favorable position for developing more fundamental system improvements.

During the reporting period our system development work has taken place within the frame of the IBM system design and in close cooperation with the IBM personnel attached to NDPC. The most interesting parts of this work will be discussed in some detail, and it is considered proper to start with the data processing systems.

1. The Detection and Event Processor

The detection algorithm implemented at NORSAR is very simple, and is essentially restricted to an SNR test on the array or subarray beam level. On the other hand, as more than 300 array beams are formed on-line, the detection processor is rather complex. We have here participated especially in making the programs more efficient and in the optimum choise of detection algorithm and filter parameters. These topics will be dealt with in greater detail in later sections.

The performance of the Event Processor (EP) which handles the routine analysis of events reported by the Detection

Pr:"essor (DP), is strongly dependent on typical seismic parameters like steering delay corrections, observed wavefront velocities, dominant signal periods, signal coherency across the array etc. Henceforth, we became very early involved in the parameterization of EP which is so far mainly based on analysis of Plan D data. With the completion of the field installations signals recorded by the whole array became available so work has already started on updating the above parameter set, emphasizing time delays and velocity vector corrections.

The Event Processor is primarily designed for automated analysis of events detected by the array. The quality of the EP results here is somewhat dependent on SNR and the complexity of the signals at hand, so a daily, visual inspection and supervision by an analyst of the event analysis is required. Special working routines have been established, and an event summary is edited daily for NDPC staff use. Moreover, we are planning to circulate in Aug/Sep a weekly NORSAR bulletin to interested institutions and seismologists. A likely bulletin setup is given in Appendix I.

2. LP - Analysis System

Texas Instrument (TI) has developed a sophisticated software package for analysis of long period (LP) waves recorded at large arrays like LASA, ALPA and NORSAR. E. Husebye and F. Ringdal spent approximately 4 weeks at SAAC, Alexandria in early spring this year for training in usage and preparing implemention of the off-line version of the TI package at NDPC. The above task was successfully completed in June, and includes creation of special NORSAR Low Rate Tapes required for data input to the LP programs.

Visual inspection of analog records prior to analysis is considered essential for several reasons. First of all, the scientist wants to be sure that the type of signals under investigation, is actually recorded by the array, and second, that faulty sensors do not impair the final results. This especially holds for LP instruments which are less stable than the SP seismometers. A possible solution to the above problem is the usage of Develocorders which is limited to the recording of 8 sensor channels per instrument unit. However, it is considered a better idea to use the Experimented Operation Console (EOC) for display of recorded signals. We are presently working on a scheme which would permit off-line display of any sensor trace stored on high or low rate data tapes.

3. High Frequency Analog Filter

For short periodic signals recorded at NORSAR a sampling rate of 20 Hz is used, while the analog, anti-aliasing filters installed in the SLEM units have the 3 dB cut-off points at 4.8 Hz. With the above recording setup we may possibly lose significant source information as NORSAR P-waves are characterized by relatively much high-frequency signal energy. As part of an investigation of this problem Mr. Handsaker/ESD proposed temporary installation at one subarray of different analog filters having the 3 dB cut-off point at 8 Hz. Filters of the latter type were implemented at subarrays 03C in the end of May, 71 and will be transferred in Aug to subarray 08C. Preliminary analysis indicate the existence of a significant amount of high-frequency signal energy, i.e. above 4 Hz, but the spectral difference between 03C and the other subarrays is small in the whole frequency range. Moreover, high frequency signal energy is easily lost during beamforming, even on the single subarray level.

4. Seminar on Seismology and Seismic Arrays

A formal opening ceremony of the NORSAR array is scheduled for November 1971, and will be combined with a seminar on Seismology and Seismic Arrays. In the latter case, invitations have been sent to individual seismologists and research institutions in Europe and North America.

III RESEARCH TOPICS

The research activities in the reporting period have been focused on NORSAR software system parameterization and array evaluation. Most of the events used in analysis, were recorded during the Plan D interim operation of the array. At that time only 18 SP sensors from different subarrays were operative. As mentioned previously, the whole array became operational in Feb 71, but only a small number of events from the latter period has been analysed so far. It should be noted that computer program modifications due to a larger data base and a new high rate tape format are somewhat time consuming.

1. Errors in Time Delay Measurements

Simple delay and sum of sensors in a seismic array is an effective method for noise suppression. However, unless precise steering delays are available, much of the signal energy is lost during the beamforming process too. We have investigated possible error sources in time delay measure-

ments, which in case of NORSAR is based on an iterative cross-correlation procedure. Parameters perturbed are correlation window length and positioning, signal frequency content and signal-to-noise ratio (SNR). The results obtained (Bungum & Husebye, 1971) indicate that relatively low frequency waves and using the very first part of the P-signals give the most reliable and stable time delay values. High frequency band pass filtering improves SNR, but signal correlation and the precision in beam steering correction decrease. Significant loss of high frequency energy during beamforming seems to be unavoidable, and this result has been confirmed by frequency domain analysis as will be demonstrated in a later section.

2. Beam Steering Delay Corrections and Mislocation Vectors

To avoid excessive signal losses during the NORSAR event detection processing, special steering delay corrections must be an integrated part of the on-line system. Another aspect is the mislocation vectors which represent the difference between NORSAR's event locations and those reported by NOAA. The latter information is required for removing biased errors in estimated azimuth and epicentral distance based on NORSAR data alone.

The basic data needed for calculating steering delay corrections and mislocation vectors are relative P-arrival times across the array for a large number of properly distributed events and the corresponding focal parameters, say, as reported by NOAA. In the former case, the measurements are computerized and an iterative cross-correlation procedure is used to ensure proper signal alignment, (Bungum

& Husebye, 1971). NORSAR event location is based on observed P-wave velocity across the array and direction of approach of the wavefront. These parameters are easily obtained by a least squares fitting of a plane wavefront to the observed arrival time.

The steering delay correction parameters are defined as the difference between observed and calculated arrival times across NORSAR. The reference model used, is that corresponding to Herrin's 1968 tables. Altogether, 172 events have been used in the above analysis, but the steering delay corrections and mislocation vectors actually implemented in the processing system are based on only 53 events. The reason for this is primarily that a large number of the "excellent" events is concentrated in a few very active seismic regions. It should be noted that presently 331 NORSAR beams are deployed. This means that only exceptionally will the actual beam locations match those of the events used in this analysis. The required interpolation procedure is linear and performed in a plane fitted through a set of three event correction points. For convenience these calculations are tied to inverse velocity coordinates instead of the conventionally used latitude and longitude.

The Plan D sets of beam steering corrections and mislocation vectors presently implemented in the Event Processor are not quite satisfactory due to the small number of events used, and the fact that data from only 18 subarrays were available. Accordingly, we plan to update the DP and EP correction files at the end of this year. This will include a complete new set of time delays in DP and a reconsideration of the present beam deployment. Finally, we should like to remark that the above work was and is a joint undertaking by IBM/SAAC and NDPC staff.

3. Earth Structure and NORSAR Travel Time Anomalies

From a seismological point of view the most interesting aspects of travel time anomalies are the corresponding structural inhomogeneities. The inversion of time delays in terms of velocity anomalies is difficult as there is no unique solution to this problem. In case of NORSAR we would intuitively expect that this effect to some extent is related to the crustal structure in the array site area. In view of the ambiguities involved in interpretation of time delays, we decided on the following approach. If the delays are at least partly of local origin, then some trend of regularity in the observed data should exist. According to Larner (1969) a good idea might be to project the individual subarray time anomalies into a trend plane and choosing the proper trend direction in a least squares sense, i.e., the azimuth where the sum of squared differences between consecutive observation points is the smallest possible. This type of analysis has been performed on Plan D time delay and signal power observations. Typical results obtained here, based on average values of around 130 events in the teleseismic distance range, are displayed in Fig 1 and 2. Using more regionalized sample populations, a few exceptional cases gave evidence for a secondary trend direction of azimuth around 50 deg., or roughly normal to the former. The dominating trend direction is parallel to the Oslo Graben and the continental margin. The above results indicate two-dimentional structures beneath the array, as also proposed by Kanestrøm & Haugland (1971).

4. Location Error Vectors

Travel time anomalies across NORSAR may be taken as a function of random and biased observational errors. The latter explains the systematic, regional dependent mis-locations of recorded events, which are removed in EP by introducing the previous discussed inverse velocity corrections. The problem, which we have tried to answer in a quantitative way, is whether the bias in the time delays across the array is due to structural anomalis in the siting area or dominated by source effects. The procedure used was to simulate event recording and location in the following way The model for relative P-arrival time at the individual sub-arrays is:

$$T_i = T_i(H) + CT_i(T) + T_i(R) \tag{1}$$

where T_i = arrival time at the subarray, $T_i(H)$ = arrival time predicted from Herrin's tables, $T_i(T)$ = two-dimentional trend correction as given in Fig 1, C = constant equal to 1.2, and $T_i(R)$ = random generated observational error assuming a variance of 0.1 sec. A comparison of location errors based on actually recorded events at NORSAR and simulated ones through eq (1) exhibit a reasonable agreement as seen from Fig 3 and 4. We may here conclude that the observed time anomalies across the array are to a large extent, say 50%, caused by structural inhomogeneities beneath the array.

5. Time Domain Filter Analysis

It is well known that the spectral distribution of seismic signals varies considerably from one region to another. Also, the spectral content of the noise exhibit large time variation as the array is located fairly close to the North

Atlantic ocean. This means that the signal-to-noise ratio (SNR), which is essentially the parameter used for event detection, is subject to both time and geographic space dependency. The main objective of this analysis was to find a physically realizable filter that could be applied to all incoming signals in real time. The performance of such a filter, with the requirement that it should give the best-in-average SNR for a large number of randomly selected events, should roughly match that of time-varying and regionalized filters.

The filters used were of two kinds, namely recursive Butterworth bandpass filters and sloping Lagrange differention filters. The former has the advantage of physical realizability and computational efficiency, while the latter may be used for flattening or whitening of the noise. Typical response curves of the above filters, are shown in Fig 5 and 6. Our results here show that the Lagrange filters alone do not suppress the noise efficiently enough, while a combination of Lagrange and Butterworth filter exhibit the best-in-average performance. However, if a few exceptional events are neglected, a third order Butterworth filter with a center frequency around 2.2 Hz and a bandwith of 2 Hz gives the largest SNR enhancements. Typical results of the above analysis are displayed in Fig 7 and 8. A joint consideration of performance and computational efficiency makes the above Butterworth filter the natural choise for use in NORSAR detection and event processing.

6. Event Detection Algoritm

The event detection procedure in the NORSAR system consists essentially of a near continuous signal-to-noise ratio (SNR) test on a large number of real time array beams which have been bandpass filtered for additional noise suppression. The problems of beam steering time corrections and the selection

of the best-in-average bandpass filter has been discussed in previous sections.

The mathematical formulation of the detection algorithm in use, is as follows:

$$STA(t) = \sum_{i=t-IW+1}^{t} \left| S(i) \right| \qquad (2)$$

where t = STA sampling time, S(i) = array beam amplitude and IW = integration window length.

$$LTA\ (t') = (1-2^{-\eta})\ .\ LTA\ (t'-IW)+2^{-\sigma}.\ STA(t'-IW) \qquad (3)$$

where t^1 = LTA sampling time, and the parameters $(\eta,\sigma) = (5,1)$ outside detection state (no signal present) and $(\eta,\sigma) = (4,0)$ in detection state. The STA is updated more frequently than LTA which means that t may differ from t^1. The ratio STA/LTA is computed every time STA is updated. When this ratio exceeds the detection threshold (THR) a certain number Q of consecutive times, a detection is declared (see Fig 9).

The analysis of the NORSAR detection process has mainly been focused on the problem of determining the best combination of STA window length (IW), STA updating interval (IUP), and the event declaration parameter Q.

We have used both NORSAR recordings and simulated data in the analysis. In the latter case Gaussian noise (before detection processing filtering) was generated by a random

number routine, while P-waves were taken as sinus modulated Fourier signals. The advantage of this approach is large data samples and that signal occurence is always known. The method used, was to determine the receiving operating characteristics (ROC) for each detector or parameter combination, and then decide which one is the best. The ROC is a plot of the probability of detection of signal, relative to the corresponding probability of false alarm. The detector that for a specified false alarm rate had the largest probability of detecting a signal, was chosen as the best one. ROC-curves for some of the simulated detector parameters are displayed in Fig 10 . The set IW = 1.2, IUP = 0.4 - 0.6 and Q = 1 gave the best parameter combinations.

To ensure validness of the above results the detector was tested using real data. In this case we made relative intensive studies of individual events, concentrating on the STA/LTA ratio as a function of time (see Fig 11). This type of information is useful for calculating the change in the STA/LTA threshold from one parameter combination to another using the constraint that the detection capability remained constant.

An important problem in event detection is the probability of false alarms as a function of the STA/LTA ratio. In case of NORSAR the number of event detection tests performed during a 24 hour interval amounts to ca. $50 \cdot 10^6$. Results obtained here, based on real data, are presented in Fig 12. The resolution of the calculated cumulative distributions of STA/LTA is at best 0.13, roughly equivalent to three times the standard deviations (SD) in a Gaussian population. To avoid system saturation a false alarm rate around 5 times the SD parameter must be considered, but no experimental data are available for this extreme range and extrapolation is hardly

valid. However, the operative performance of the NORSAR Detection Processor indicates that extremal STA/LTA values have a non-Gaussian distribution.

Software limitations necessitate the use of a "linear" power detector and not a squared one which is optimal according to theory. Both types of detectors have been simulated, and for small signals the difference in detection capability is negligible (see Fig 13).

Finally, it should be noted that the event detector analysis gave the same results whether real or simulated data were used. This means that the noise and signal models considered gave a good approximation to actual NORSAR recordings.

7. Frequency Domain Analysis

Signal spectra and coherence has been estimated for the 22 Plan D events presented in Table 1. The computational procedure used, is based on the auto- and cross-correlation functions. The signal time window was 6.4 sec (10 Hz sampling) and the maximum lag in correlation 15%. Following Blackman & Tukey (1959) the number of degrees of freedom k can, for a reasonable smooth spectrum, be estimated as:

$$k = 2 \cdot \frac{Tn'}{Tm} = 2 \quad \frac{Tn}{Tm} - \frac{1}{3} \qquad (4)$$

where Tn = signal length and Tm = maximum lag. In our case $k = 6$ which is equivalent to a 90% confidence interval of ca 10 dB for the spectral estimate on the single sensor level.

In order to estimate the confidence interval for coherence, we refer to the tables of Amos & Koopmans (1963). Their results for k = 6 are given in Fig 14 and shows that at a 90% confidence interval, an observed coherence of 0.8 reflects

a true coherence somewhere in the interval between 0.60 and 0.94. However, spectral estimates based on the average over a number of N sensor would have an improved stability approximately proportional to $N^{-\frac{1}{2}}$.

Results of the coherence analysis are presented in Fig 15 - 17, and brief comments are as follows. In the range 20 - 100 km observed signal coherence does not exhibit significant distance dependence, i.e., subarray site anomalies seem to dominate contrary to the expected effect of sensor separation. The coherence function peaks around 1.0 Hz (typical value 0.7 units) and then slowly taper off with increasing frequencies. The above results are in reasonable agreement with corresponding time domain observation (same event population) which gave a beam/sensor and sensor/sensor correlation of 0.76 and 0.62 units respectively for a band-pass filter of 0.8 - 2.8 Hz and a 6.4 signal window. It should be noted that signal coherence vary considerably from one event to another on the array level, while more stable and significantly higher values are observed on the subarray level (see Fig 17).

The spectral analysis clearly demonstrate the increasing P-signal energy loss during beamforming as a function of frequency, and results based on Plan D events are displayed in Fig 18. A corresponding loss of ca 2 dB was obtained by time domain beamforming, and is considered reasonable as the Plan D event spectra have the maxima around 1.0 - 1.5 Hz. Moreover, observed P-signal power exhibit large non-random variations across the array as demonstrated in Fig 19.

The frequency domain analysis of NORSAR events has continued after the array became operational, thus ensuring a

more representative data base than the "excellent" Plan D events (Table 1) previously used. We have concentrated on various kinds of power spectra which are related to processing methods and system evaluation. For example, beam spectra represent the square of the sum of sensor amplitude spectra, while the spectraform represents the average of sensor power spectra. For more details on computational methods and physical implications, the proper reference is a paper by Lacoss and Kuster (1970).

Different types of spectra and spectral ratios are presented in Fig 20 - 23, and brief comments are as follows. Signal loss during beamforming on the array level may be very large, especially for frequencies above 2 Hz (Fig 20 - 22). In the latter case, the expected gain in SNR amounting to 21.2 dB for NORSAR is partly compensated by the suppression of the high frequency signal components. On the subarray level the situation is somewhat different as severe signal losses commence around 3 Hz. The above results which are based on a signal window length of 6.4 sec, are considered typical for the NORSAR array. It should be noted that smaller beam signal losses are observed for window lengths of 3.2 sec. Moreover, during the on-line event detection process much shorter signal lengths are used as discussed in the previous section. Anyway, the essence of the above results is that a spectraform method may be a viable alternative to beam-forming - above a certain signal frequency - for detecting small events. Moreover, the spectraform processing gives a smaller noise variance, and thus simplify the false alarm problem discussed in the previous section. Another factor to be considered, is the noise level which is strongly dependent on the weather situation in the North Atlantic Ocean (see Fig 23).

8. P-velocity Discontinuities in the Earth's Mantle

The gross structure of the earth's interior is fairly well known, but we are still lacking information on the finer details, i.e. structural discontinuities of higher orders. We have investigated this problem using the Fennoscandian continental array and found evidence for vertical and lateral P-velocity discontinuities in the mantle (Husebye et al, 1971). The main results obtained are displayed in Fig 24.

9. Future Plans

The system parameterization work will continue in order to improve the beam steering correction files and event location. Minor modification of the present beam deployment will also be implemented. Evaluation of NORSAR's event detection and location capabilities is in progress. Both processed data like epicenter parameters of recorded events and more original data like beam and spectraform spectra are considered. The reason for the above approach to the evaluation problem may be illustrated by the following example. Presently, it seems that NORSAR's event detection capability is lesser than that of LASA, but also lesser than in general expected, which the spectral analysis (section III,7) indicate that improved performance could possibly be obtained by other types of detector processing schemes. In short, we must differentiate between the joint performance of the array and the present software system and the potential of the array itself. Corresponding evaluation work of the LP data will also be undertaken.

REFERENCES

D.E. Amos and L.H. Koopmans: Tables of distribution of coherence for stationary bivariate Gaussian process, Sandia Corp. Monograph, SCR-483, 1963.

R.B. Blackman and I.W. Tukey: The measurement of power spectra, Dower Publications, Inc., New York, 1959.

H. Bungum and E.S. Husebye: Errors in time delay measurements, Pure and Appl. Geophys., 91, pp 56 - 70, 1971.

E.S. Husebye, R. Kanestrøm and R. Rud: Observations of vertical and lateral P-velocity in the earth's mantle using the Fennoscandian continental array, Geophys. J.R. astr. Soc., 26, pp 14, 1971.

R. Kanestrøm and K. Haugland: Crustal structure in south-eastern Norway from seismic refraction measurements. Sci. Rep., no. 5, Seismological Observatory, Univ. of Bergen, 1971.

R.T. Lacoss and G.T. Kuster: Processing a partially coherent large seismic array for discrimination, Tech. Note 1970 - 30, Lincoln Lab., Mass. Inst. Tech., Nov. 1970.

K. Larner: Near receiver scattering of teleseismic body waves in layered crust-mantle models having irregular interfaces, Ph.D. thesis, Mass. Inst. Tech., 1969.

TABLE CAPTION

Table 1 : The 22 events used in analysis.

EVENT NO	ARRIVAL TIME		MB	LAT	LONG	REGION
1	16 JAN 1970	08.15.27.9	5.6	60.3N	152.7W	SOUTH ALASKA
2	20 JAN 1970	00.49.08.9	5.1	53.8N	163.5W	UNIMAK ISLANDS
3	27 JAN 1970	10.59.40.1	5.1	34.9N	101.3E	TSINGHAI, CHINA
4	29 JAN 1970	06.14.58.8	5.1	36.0N	140.4E	NEAR EAST OF HONSHU
5	31 JAN 1970	11.54.21.2	5.3	4.1N	96.0E	NORTHERN SUMATRA
6	06 FEB 1970	00.22.14.0	5.6	54.6N	163.6E	OFF EAST KAMCHATKA
7	07 FEB 1970	23.47.53.5	5.0	47.3N	154.0E	KURILE ISLANDS
8	12 FEB 1970	02.01.25.1	5.4	29.4N	81.6E	NEPAL
9	16 FEB 1970	21.54.50.8	5.3	25.2S	178.3E	SOUTH OF FIJI
10	17 FEB 1970	05.59.10.6	5.9	9.8N	126.0E	MINDAN, PHILIP. ISLANDS
11	19 FEB 1970	07.20.31.3	5.5	27.4N	94.0E	EAST INDIA
12	27 FEB 1970	07.19.05.2	6.0	50.1N	179.6W	ANDREANOF ISLANDS
13	11 MAR 1970	22.48.50.8	6.0	57.5N	153.9W	KODIAK ISLANDS REGION
14	13 MAR 1970	17.39.16.0	4.6	51.7N	175.3E	RAT ISLANDS, ALEUTIANS
15	17 MAR 1970	01.37.15.6	4.9	26.3S	177.0W	SOUTH OF FIJI
16	22 MAR 1970	02.02.48.8	5.4	21.7N	73.0E	INDIA
17	26 MAR 1970	19.11.33.3	6.5	37.3N	116.5W	NEVADA
18	27 MAR 1970	04.39.16.3	5.2	5.6N	77.6W	NEAR WEST COLOMBIA
19	27 MAR 1970	05.10.20.0	5.2	49.8N	78.0E	EAST KAZAKH
20	28 MAR 1970	03.56.56.2	5.1	39.6N	75.4E	SOUTH SINKIANG
21	07 APR 1970	05.46.47.6	6.4	15.8N	121.7E	LUZON, PHILIPPINES
22	07 MAY 1970	04.20.42.8	5.1	14.6N	93.6W	OFF CHIPAS, MEXICO

FIGURE CAPTIONS

Fig 1; Relative time delays across the NORSAR array. The given values are the average of the 130 Plan D events in the teleseismic distance range.

Fig 2; Relative time delays and NORSAR Plan D configuration. MOHO depth contours as presented by Kanestrøm & Haugland (1971) are outlined. The subarrays 01A, 03B, 04B and 05B are not included in the figure.

Fig 3; Error in azimuth as observed and predicted from a simple time delay model.

Fig 4; Error in slowness as observed and predicted from a simple time delay model.

Fig 5; Amplitude response of Lagrange sloping filters used in analysis.

Fig 6; Phase and amplitude response of a third order Butterworth recursive filter having a passband from 1.0 - 3.0 Hz for a 10 Hz sampling rate.

Fig 7; SNR in dB for the array beam using both Lagrange and Butterworth filters for additional noise suppression. The broadness of the main beam lobe is noteworthy. The event used, no. 18 in Table 1, is a presumed explosion in eastern Kazakh.

Fig 8; SNR in dB for the array beam using only the Butterworth filter for additional noise suppression. The event used, no. 18 in Table 1, is a presumed explosion in eastern Kazakh.

Fig 9; Working principle of the NORSAR detection processor. STA = short term average, LTA = long term average. The line above the STA/LTA curve indicates detection state, while the line crossing the curve is the threshold.

Fig 10; Receiver operating characteristics determined from simulated data. The numbers in brackets are STA integration length in dsec, STA updating rate in dsec, and event declaration parameter Q.

Fig 11; Integrated STA/LTA values as a function of time when the system is in "detection state". The STA window length was 1.2 sec, and the earthquake analysed occurred in Sumatra 06/31/70.

Fig 12; Cumulative distribution of the STA parameter for a single sensor and based on a noise sample of 1 hour, July 23, 1970. STA integration length and updating interval was 0.6 sec. The three curves correspond to declaration parameter or Q values of 1,2 and 3 respectively. The 99 - 100% distribution interval is enlarged.

Fig 13; Receiver operating characteristics for linear and square detectors calculated from simulated data.

Fig 14; Coherence confidence area of 90% for six degrees of freedom.

Fig 15; Average coherence between single sensors for different frequencies as a function of sensor separation. The data base is the 22 events in Table 1.

Fig 16; Average coherence for beam/sensor and sensor/sensor combinations as a function of frequency for the 22 events listed in Table 1.

Fig 17; Results of coherence analysis for 4 events. Event I: Kurile Is., 22 May 1969; Event II: Fox Is., 7 May 1969; Event III: Lake Aral, 6 Dec 1969; Event IV: Kazakh expl., 30 Nov 1969. Subarray 14C corresponds to the experimental array Øyer, while NORSAR is NORSAR Plan D configuration.

Fig 18; Average beamforming loss as a function of frequency. Data base is the 22 events listed in Table 1.

Fig 19; Relative signal power across the NORSAR array. The given values are the average of ca 130 Plan D events in the teleseismic distance range.

Fig 20; Array beam and spectraform spectra for an earthquake in Szechwan 08/16/71.

Fig 21; Beamform-spectraform spectral ratio for an earthquake in Szechwan 08/16/71.

Fig 22; Signal-to-noise ratio for beamform and spectraform spectra for an earthquake in Szechwan 08/16/71.

Fig 23; Observed noise spectra at different days of the year. Variations in the noise level (LTA range) and detection processor filter setting are marked.

Fig 24 A new P-velocity model for the taper mantle. Observed lateral velocity variation is represented by the NOR1 and NOR2 models respectively. The standard model of Jeffreys-Bullen (1958) is included.

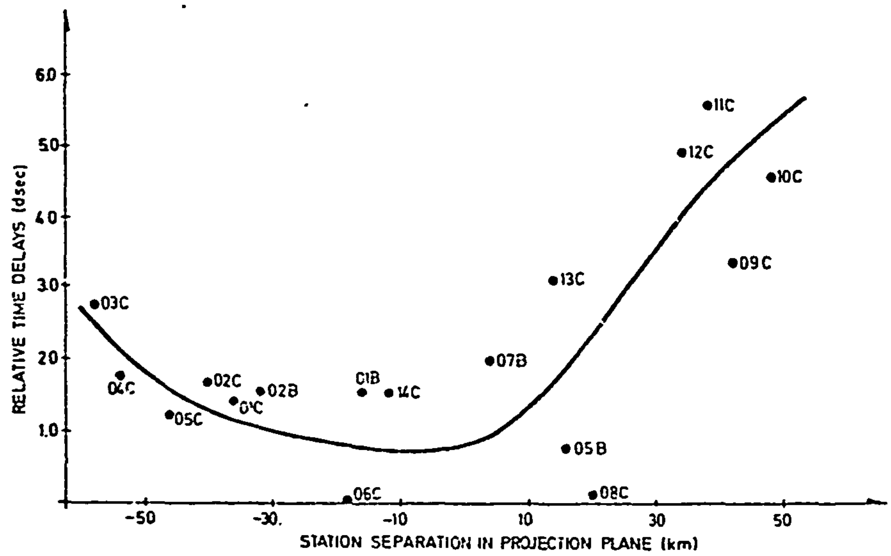

Figure 1

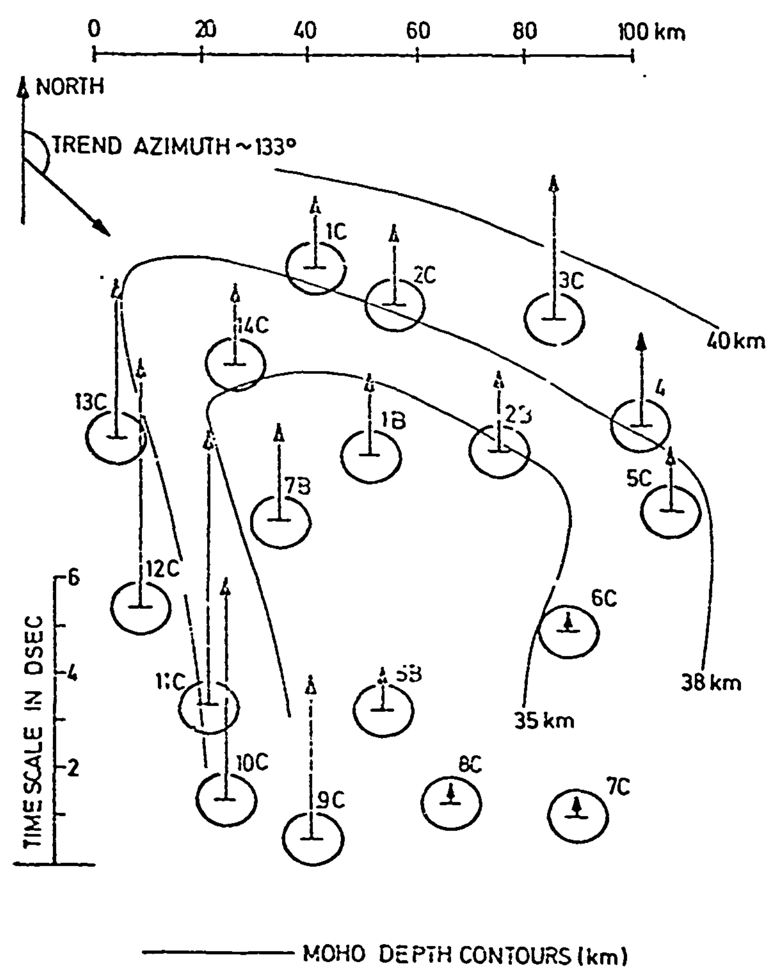

Figure 2

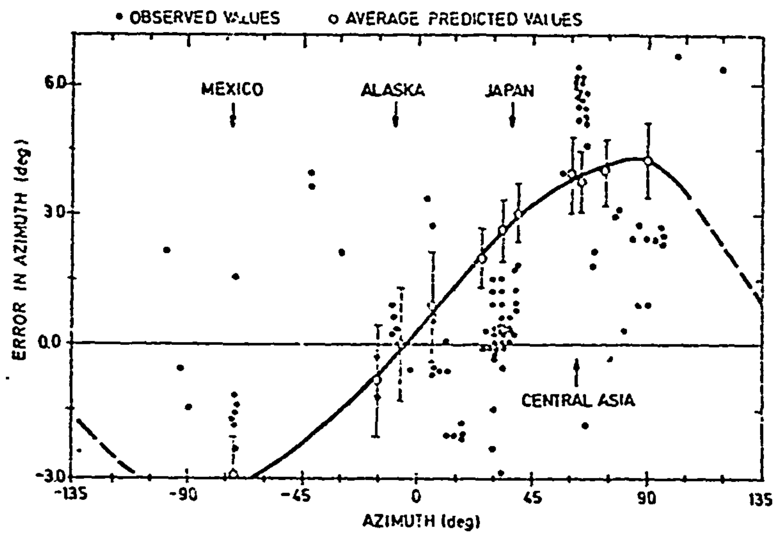

Figure 3

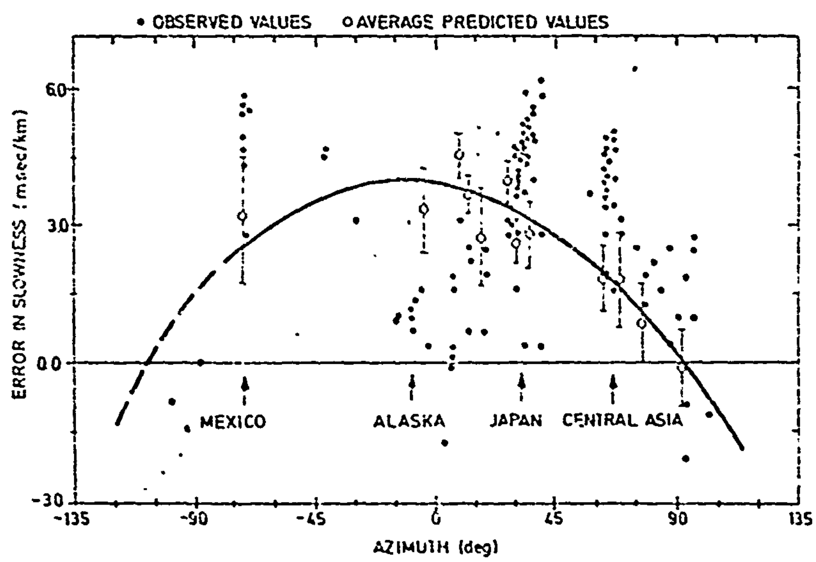

Figure 4

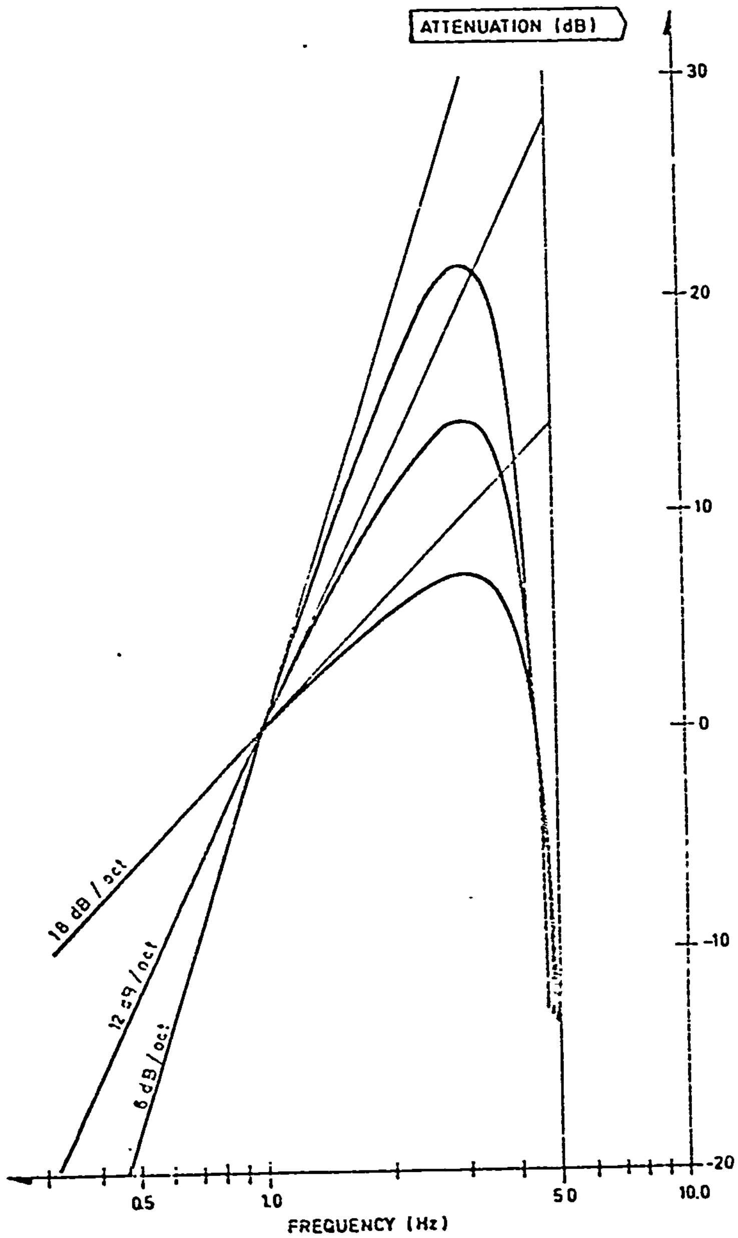
ATTENUATION (dB)
30
20
10
0
-10
-20
18 dB / oct
12 dB / oct
6 dB / oct
0.5
1.0
5.0
10.0
FREQUENCY (Hz)

Figure 5

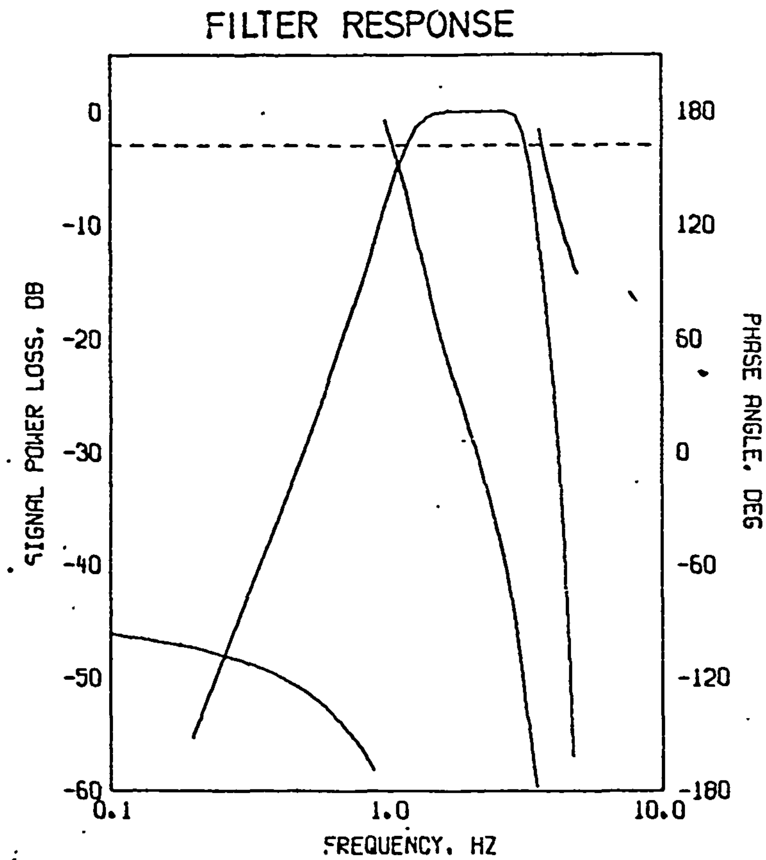

Figure 6

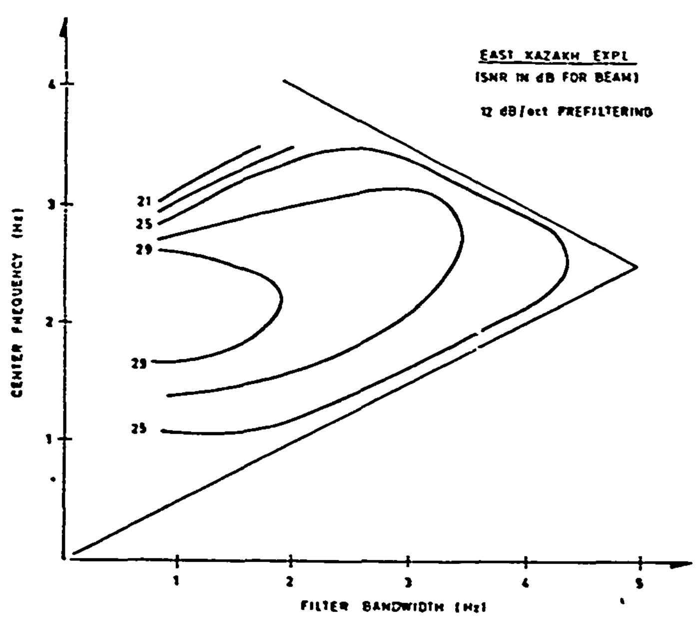

Figure 7

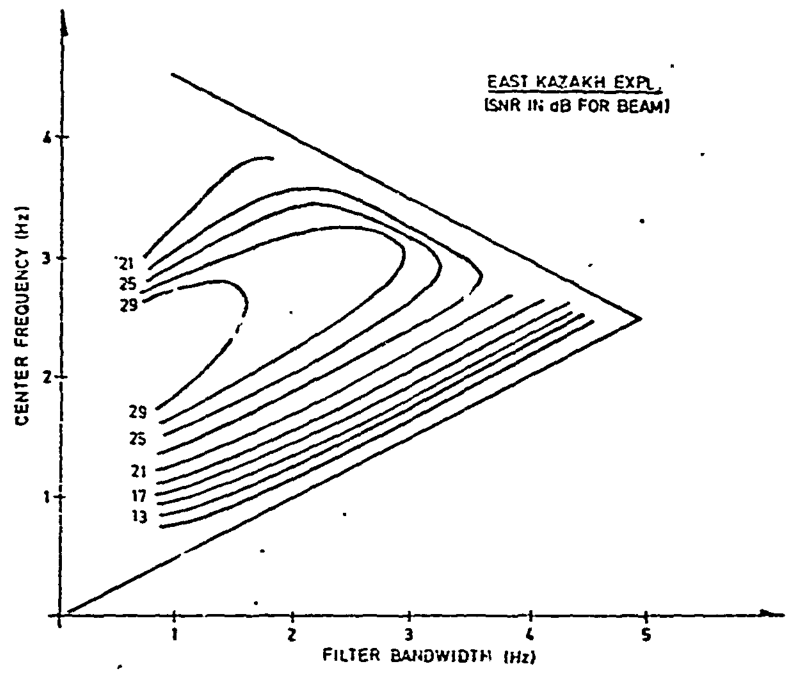

Figure 8

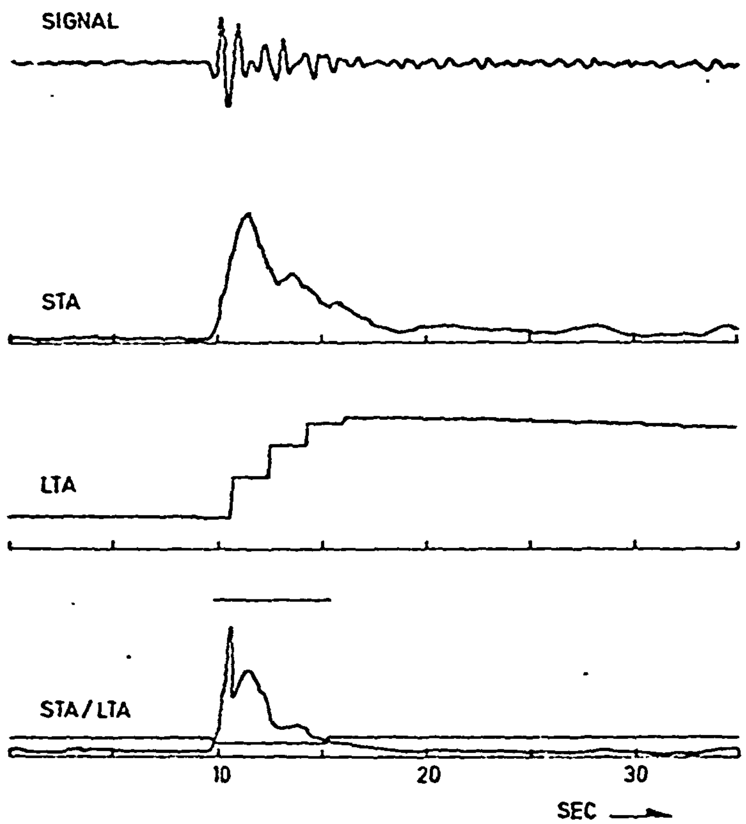

Figure 9

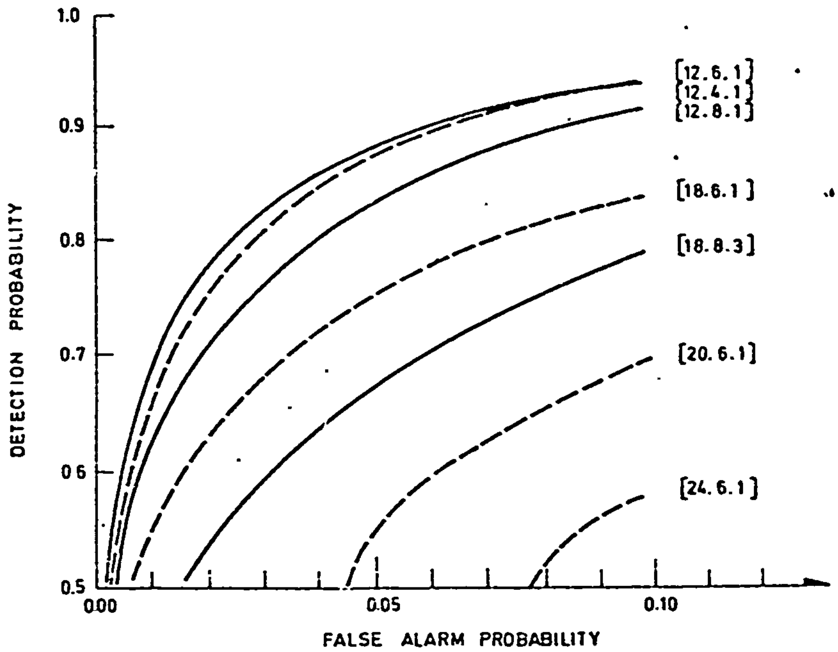

Figure 10

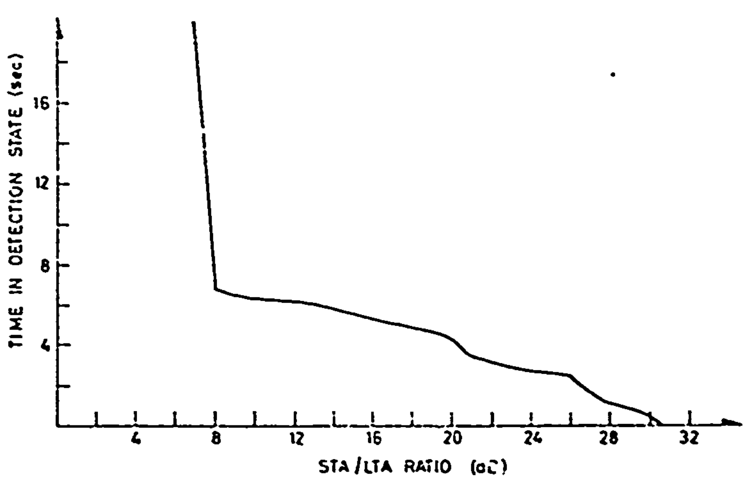

Figure 11

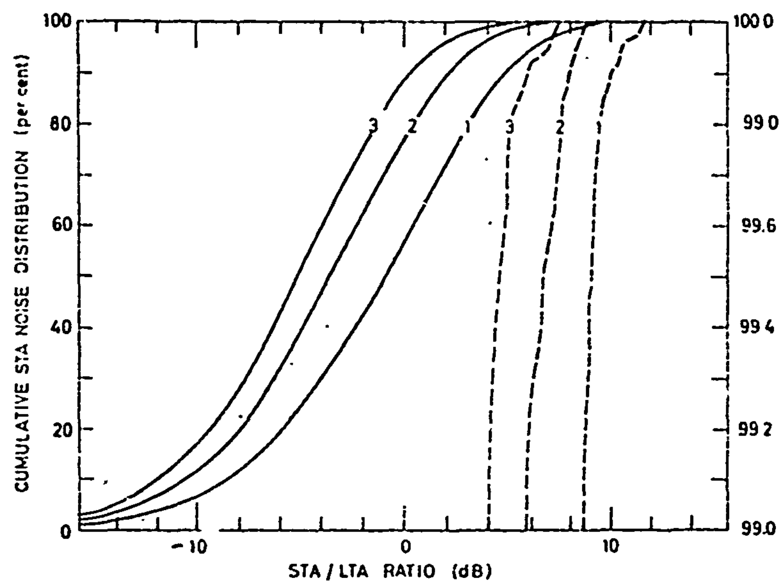

Figure 12

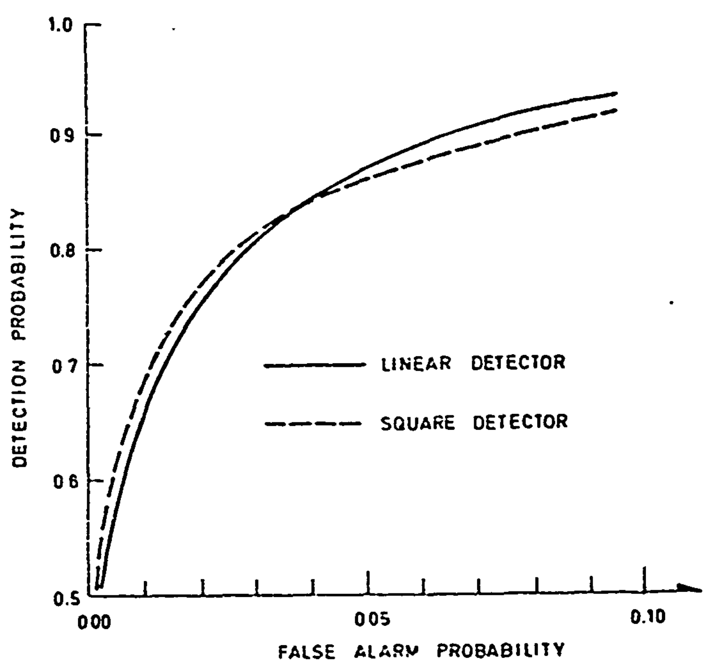

Figure 13

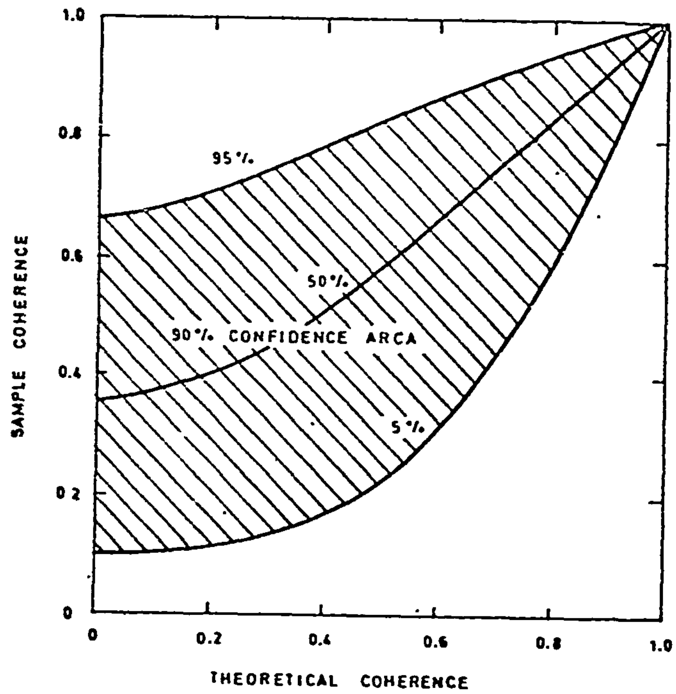

Figure 14

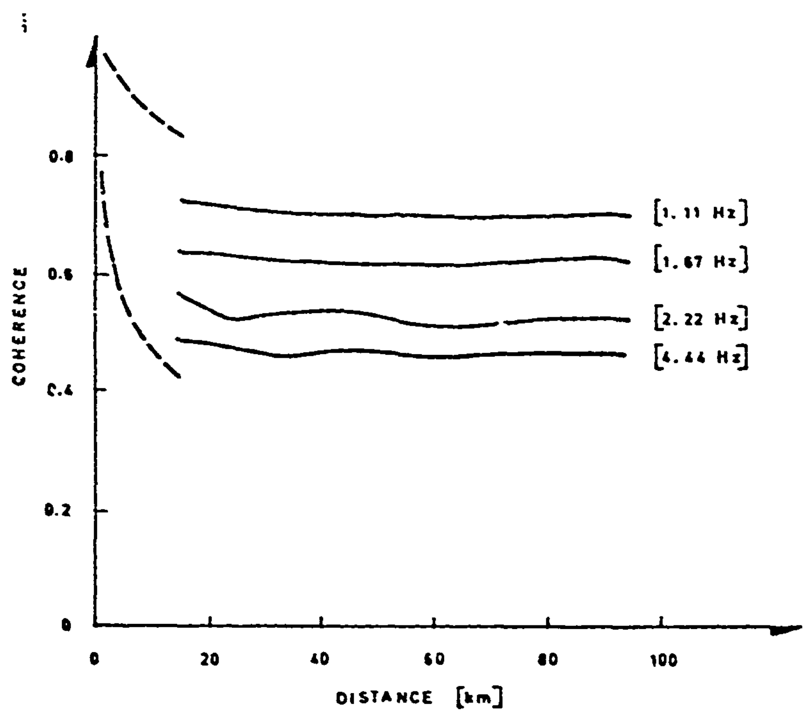

Figure 15

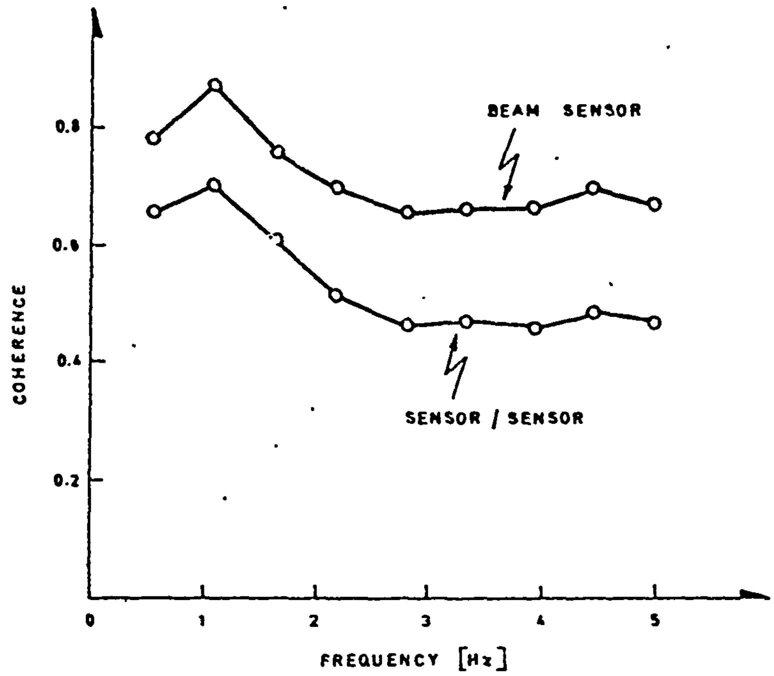

Figure 16

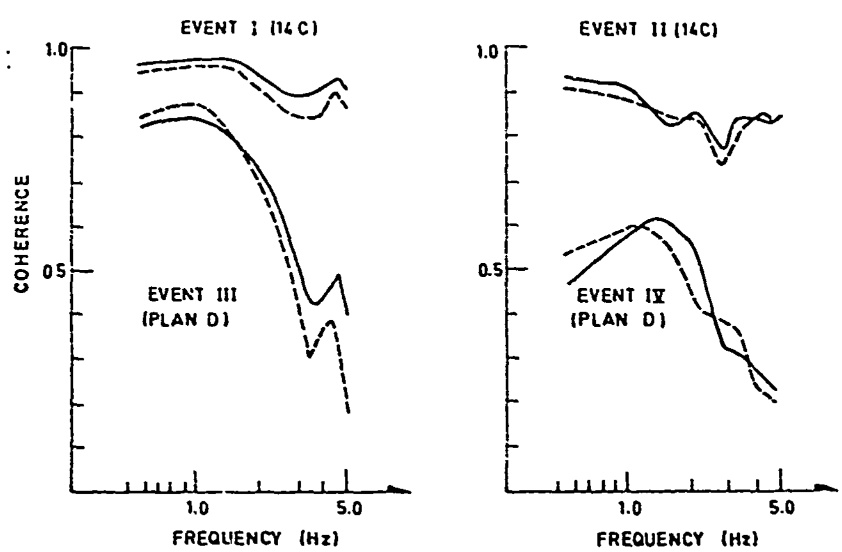

Figure 17

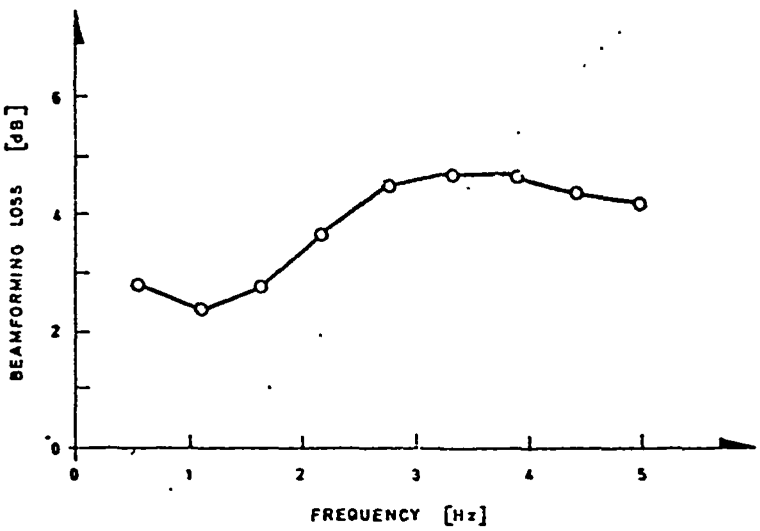

Figure 18

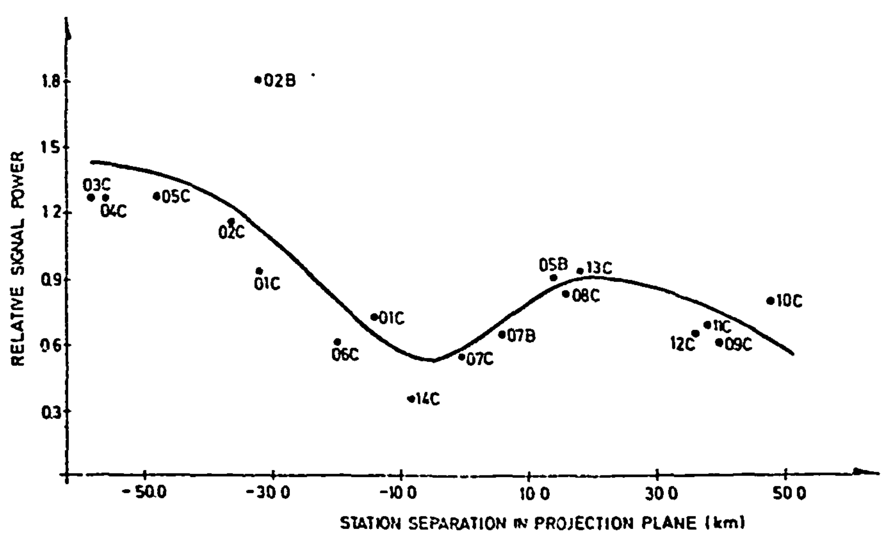

Figure 19

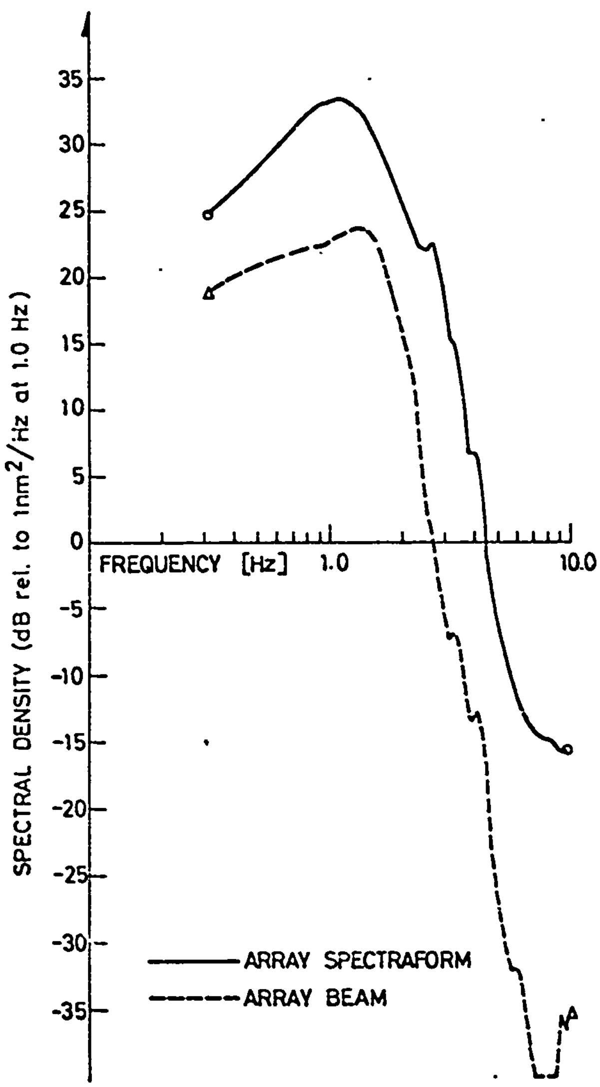
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
SPECTRAL DENSITY (dB rel. to 1nm^2/Hz at 1.0 Hz)
FREQUENCY [Hz]
1.0
10.0
ARRAY SPECTRAFORM
ARRAY BEAM

Figure 20

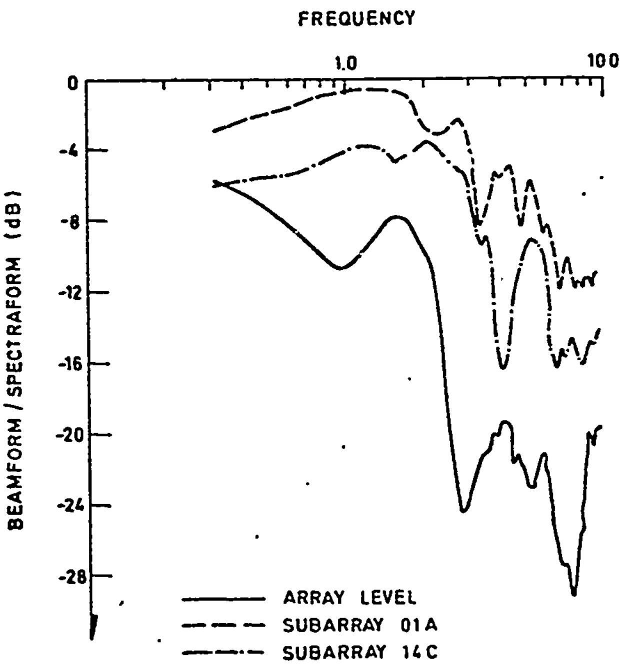

Figure 21

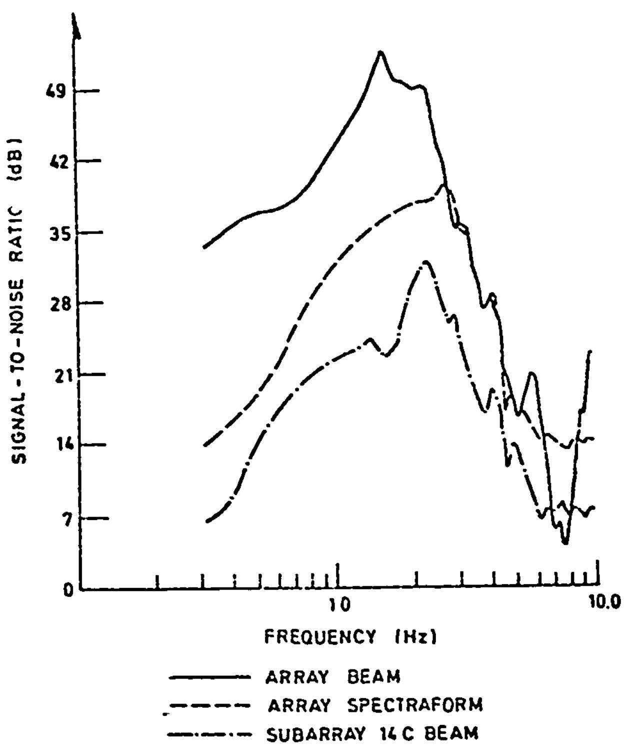

Figure 22

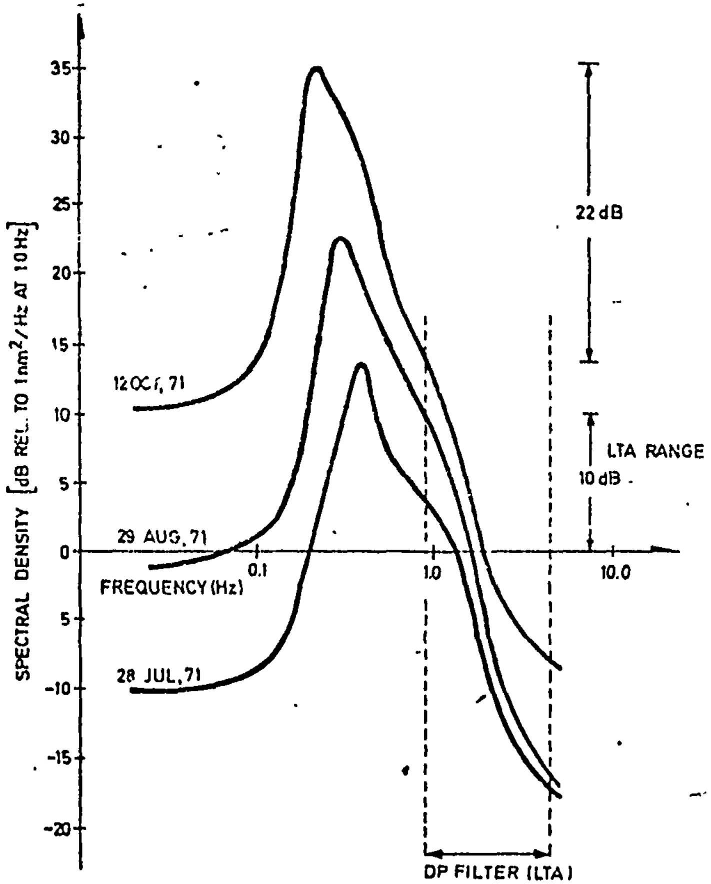

Figure 23

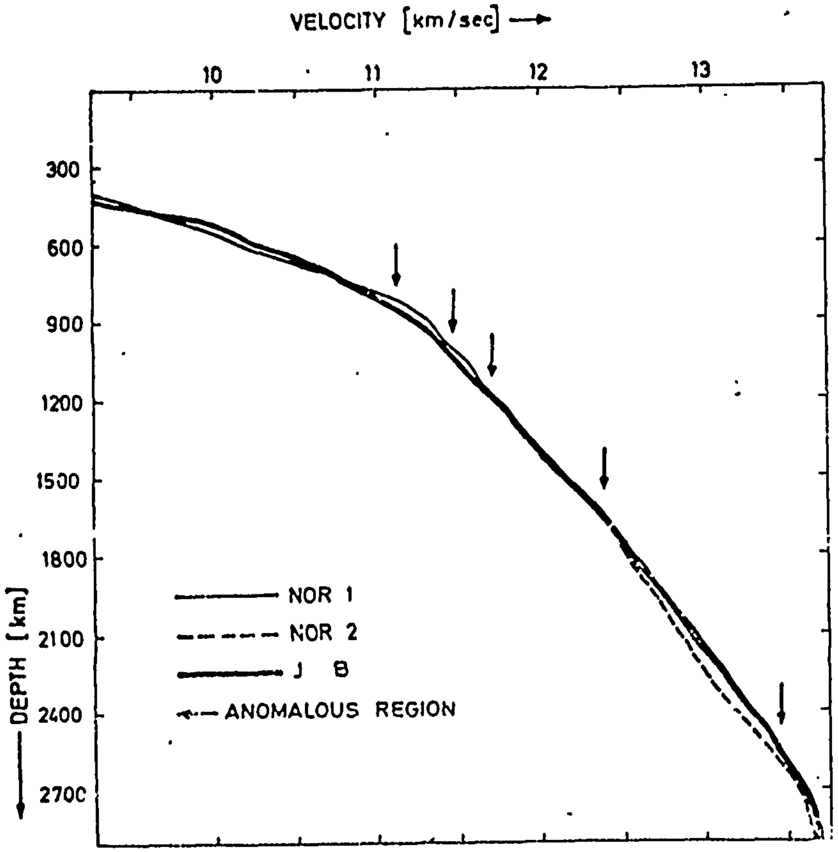

Figure 24

NORSAR SEISMIC EVENT SUMMARY   ISSUED 21 JUL 1971

FOLLOWING EXPLAINS THE ENTRIES IN THE NORSAR EVENT SUMMARY

ARRIVAL TIME	ARRIVAL TIME (GMT)
REF	REFERENCE SUBARRAY FOR ARRIVAL TIME
PHS	PHASE NAME
AMP	ZERO-PEAK AMPLITUDE (NM)
PER	PERIOD (SEC)
VEL	APPARENT PHASE VELOCITY (KM/SEC)
DIR	DIRECTION OF WAVEFRONT APPROACH (DEG)
DEL	DISTANCE TO EPICENTER (DEG)
OR. TIME	ORIGIN TIME (GMT)
LAT	EPICENTER LATITUDE (DEG)
LONG	EPICENTER LONGITUDE (DEG)
MB	BODY WAVE MAGNITUDE
REGION	REGION NUMBER AND NAME (FLINN AND ENGDAHL)

PROCESSED INTERVAL(S)

13 JUL 0000 - 13 JUL 0706	15 JUL 0932 - 15 JUL 1500
13 JUL 1108 - 14 JUL 1027	15 JUL 1543 - 16 JUL 0349
14 JUL 1128 - 14 JUL 1624	16 JUL 0740 - 17 JUL 0718
14 JUL 1828 - 15 JUL 0738	17 JUL 0818 - 17 JUL 1838
15 JUL 0840 - 15 JUL 0923	17 JUL 1841 - 19 JUL 2400

DATA RETENTION TIME IS 9 MONTHS

NTNF/NORSAR
P.O. BOX 51
N-2007 KJELLER
NORWAY

ARRIVAL TIME	REF	PHS	AMP	PER	VEL	DIR	DEL	OR. TIME	LAT	LONG	MB	REGION	
16 JUL 20.27.41.5	01A	P	3.0	0.6	13.8	94	48	20.19.06	35N	75E	4.3	302	EASTERN KASHMIR
16 JUL 21.52.54.0	01A	P	34.4	1.5	23.3	299	86	21.40.19	15N	98W	5.2	65	OFF COAST GUERRERO, MEX.
16 JUL 22.27.11.1	01A	P	22.4	1.2	18.3	42	73	22.15.44	39N	143E	5.0	229	OFF E COAST HONSHU,JAPAN
17 JUL 04.52.11.9	01A	P	7.3	1.0	19.2	44	76	04.40.26	35N	143E	4.6	229	OFF E COAST HONSHU,JAPAN
17 JUL 05.44.44.3	01A	P	141.7	1.0	17.7	90	81	05.32.33	7N	94E	5.9	704	NICOBAR ISLANDS REGION
17 JUL 05.54.40.9	01A	P	204.5	1.3	9.3	91	19	05.50.29	56N	45E	5.3	724	WESTERN RUSSIA
17 JUL 12.43.57.0	01A		3.5	0.3									LOCAL
17 JUL 15.11.24.0	01A	P	45.6	0.8	15.8	84	62	15.01.13	28N	92E	5.4	313	INDIA-CHINA BORDER REGION
17 JUL 19.39.22.0	01A	P	2.2	1.0	18.6	43	74	19.27.50	38N	143E	4.1	228	NEAR E COAST HONSHU,JAPAN
17 JUL 19.41.23.4	01A	P	7.7	1.0	18.1	42	73	19.30.00	40N	143E	4.6	229	OFF E COAST HONSHU,JAPAN
17 JUL 20.28.26.8	01A	P	40.8	1.6	15.3	245	52	20.19.23	23N	40W	5.1	402	NORTH ATLANTIC OCEAN
18 JUL 00.09.16.4	01A	P	1.9	0.5	11.7	119	27	00.03.36	42N	42E	4.2	367	TURKEY-USSR BORDER REGION
18 JUL 01.25.55.1	01A	P	1.5	0.7	16.7	84	70	01.14.45	21N	97E	4.1	296	BURMA
18 JUL 05.10.01.8	01A	P	2.7	0.8	17.4	20	63	04.59.37	54N	164E	4.2	219	OFF EAST COAST KAMCHATKA
18 JUL 07.13.17.0	01A	P	0.8	0.8									
18 JUL 08.59.42.8	01A	PKP	10.5	0.9	39.8	30	154	08.39.47	36S	180W	4.8	688	EAST OF NORTH ISLAND,N.Z.
18 JUL 11.22.49.6	01A	PKP	4.1	0.9	30.6	21	144	11.03.19	26S	178W	4.2	171	SOUTH OF FIJI ISLANDS
18 JUL 11.25.39.3	01A	PKP	5.6	1.0	35.7	25	149	11.05.57	30S	179W	4.3	178	KERMADEC ISLANDS
18 JUL 14.46.20.0	01A	P	4.3	0.9	22.0	48	95	14.33.01	17N	147E	4.9	216	MARIANA ISLANDS
18 JUL 14.50.01.8	01A	PKP	12.3	0.9	109.1	71	175	14.29.57	58S	178W	5.4	690	SOUTH OF CHATHAM ISLANDS
18 JUL 15.00.22.0	01A		2.2	1.0									
18 JUL 15.04.53.0	01A		3.5	0.9									
18 JUL 16.22.22.8	01A	P	5.6	0.9	8.9	144	18	16.18.18	45N	25E	4.1	358	RUMANIA
18 JUL 19.29.08.9	01A	P	2.3	1.1	23.3	307	88	19.16.23	17N	106W	4.3	64	OFF COAST MICHOACAN, MEX.
18 JUL 23.20.14.9	01A	P	2.5	1.0	17.8	9	67	23.09.27	52N	179E	4.1	6	RAT ISLANDS, ALEUTIANS
19 JUL 00.33.32.4	01A	PKP	10.2	1.2	40.7	55	158	00.13.27	43S	170E	5.0	161	OFF W COAST OF S IS.,N.Z.
19 JUL 00.43.49.8	01A	PKP	5.8	0.9	31.1	210	144	00.24.19	69S	80W	4.3	692	SOUTHERN PACIFIC OCEAN
19 JUL 00.59.16.6	01A	P	2.3	0.6	19.5	195	77	00.47.30	14S	9W	4.4	409	SOUTH ATLANTIC OCEAN .
19 JUL 06.28.05.0	01A	P	4.0	0.8	13.9	91	46	06.19.44	38N	76E	4.3	321	SOUTHERN SINKIANG PROV.
19 JUL 09.25.26.0	01A	P	2.8	1.1									
19 JUL 09.33.35.0	01A	PKP	4.3	1.0	25.7	15	163	09.12.47	44S	173W	4.8	689	CHATHAM ISLANDS REGION
19 JUL 12.34.38.5	01A	P	5.2	0.8	18.4	43	73	12.23.11	39N	143E	4.6	228	NEAR E COAST HONSHU,JAPAN
19 JUL 15.07.16.9	01A	PKP	6.1	0.8	41.4	68	123	14.48.25	17S	139E	5.1	594	QUEENSLAND, AUSTRALIA
19 JUL 15.17.57.9	01A	PKP	3.2	0.8	34.3	221	144	14.58.29	63S	88W	4.1	692	SOUTHERN PACIFIC OCEAN
19 JUL 15.57.41.1	01A	P	8.1	1.8	15.8	48	59	15.47.46	49N	126E	4.3	658	NORTHEASTERN CHINA
19 JUL 17.10.00.0	01A	P	2.0	1.1									
19 JUL 17.10.08.4	01A	P	34.4	1.2	18.5	64	75	16.58.33	28N	121E	5.2	664	EASTERN CHINA
19 JUL 17.37.16.0	01A	P	1.1	1.1									

APPENDIX II

H. Bungum and E.S. Husebye: Seismic arrays and data handling problems. Union Geodésique et Geophysique International, European Seismological Commission, pp. 4, 1971.

Abstract

To take full advantage of recent developments in seismological theory and sophisticated interpretation methods requires that high quality data are easily available for research purposes. As of today, the large number of seismological observatories in operation, produce a tremendous amount of quantitative data which are hardly accessible for the seismological community. The latter problem prevails even for the large aperture seismic arrays which are characterized by a new seismic observation concept, advanced recording and standardized analysis techniques. In this paper we compare different types of seismic wave recording systems, and discuss relevant data handling problems. It is concluded that array processing techniques could be adapted to ordinary station networks, requiring coordination and cooperation in seismograph operation on a regional basis. In this way data quality and accessibility could be improved, but at the same time reducing the costs involved in running the global seismic network.

H. Bungum and E.S. Husebye: Errors in time delay measurements. re and Appl. Geophys., 91: 56-70, 1971.

Abstract

Simple delay and sum of sensors in a seismic array is an effective method for noise suppression. However, unless we have precise steering delays, much of the signal energy is lost during the beam forming process too. We have investigated possible error sources in time delay measurements, using a computerized cross-correlation procedure. Parameters perturbed are correlation window length and positioning, signal frequency content and signal to noise ratio (SNR). Our results indicate that relative low frequency waves and using the very first part of the P-signals give the most reliable and stable time delay values. High frequency bandpass filtering improves SNR, but signal correlation and the precision in beam steering corrections decrease. Significant loss of high frequency energy during beam-forming seems to be unavoidable.

H. Bungum, E. Rygg and L. Bruland: Short-period seismic noise structure at the Norwegian Seismic Array. Bull. seism. Soc. Am., Vol 61, pp. 357-373, 1971.

Abstract

Power spectral analysis in frequency-wavenumber space and coherence studies in lag space have shown that the noise recorded by the short period Øyer subarray at NORSAR is critically dependent on the weather situation in the North Atlantic Ocean. In addition to the low-frequency noise from the west, there is observed 2-sec microseisms from the Baltic Sea. Because of the non-isotropic noise, the coherence is usually strongly azimuthal dependent, being represented in lag space by ellipses. Large time variations of the coherence are demonstrated.

E.S. Husebye, R. Kanestrøm and R. Rud: Vertical and lateral inhomogeneities in the earth's deep mantle. Union Geodésique et Geophysique International, European Seismological Commission, pp. 4, 1971.

Abstract

The gross structure of the earth's interior is fairly well known, but we are still lacking information on the finer details, i.e., structural heterogeneities causing higher order discontinuities in seismic wave velocities. The most fascinating aspect of this problem is the possibility of having lateral velocity variations in the deep mantle.

Support of the above hypothesis comes from recent analysis of measured $dT/d\Delta$ values (Chinnery and Toksöz 1967, Hales et al 1968, Johnson 1969) which indicates azimuth dependence in the observations themselves and the individual studies present significantly different results in certain distance intervals. A joint analysis of several types of geophysical data (Toksöz et al 1969) and P-wave diffraction studies (Phinney and Alexander 1969) also favor the existence of lateral inhomogeneities in the lower mantle. We have investigated the above problems, using $dT/d\Delta$ data which represents an efficient tool for such analysis.

H1

H. Bungum og E.S. Husebye: Aspekter ved digital seismisk analyse, Ingeniør-Nytt, No. 5, Feb. 1971.

This paper gives (in Norwegian) a brief review of the fundamental principles of exploration seismology. Emphasis is on data handling and various kinds of digital filtering techniques, wave parameter extraction and methods of interpreting seismic data.

H. Bungum, E.S. Husebye and F. Ringdal: The NORSAR array and preliminary results of data analysis. In press. Geophys. J.R. Astr. Soc., pp. 14, 1971.

Abstract

A large aperture seismic array, NORSAR, has been constructed in Norway. The project, which started in the summer of 1967, is a joint undertaking by the governments of Norway and the United States of America. NORSAR consists of 22 subarrays, each equipped with one three-component long-period and six short-period instruments. The array diameter is around 110 km, while that of a subarray is approximately 8 km. In the data centre, which is located just outside Oslo, are installed 2 IBM 360/40 computers with peripheral equipment, a special-purpose computer, and an experimental operations console. Routine tasks performed at the data centre comprise array monitoring and calibration, data acquisition, on-line event detection and off-line event analysis. In this paper we give a technical description of NORSAR, emphasizing the software aspects of the array operation, and present some analysis results of P-waves recorded at NORSAR. For example, we have found that signal power and spectral characteristics vary across the array and seem to reflect local differences in the geological structures at the subarray sites. The recorded signals are found to be broadband and to contain significant energy at higher frequencies. Observed signal coherencies vary considerably across the array and are usually independent of station separation. Within the subarrays signal coherence is high and the waveforms exhibit little scattering.

42

E.S. Husebye, R. Kanestrøm and K. Rud: Observations of vertical and lateral P-velocity in the earth's mantle using the Fennoscandinavian continental array. Geophys. J.R. Astr. Soc., 26, pp. 14, 1971.

Abstract

The gross structure of the Earth's interior is fairly well known, but we are still lacking information on the finer details, i.e. structural discontinuities of higher orders. A powerful tool in investigations of this type of problem is P-wave travel time, and specifically the parameter DT/DΔ. We have investigated this problem, taking advantage of the concept of continental arrays. Reported arrival time data (seismic bulletins) for the Fennoscandinavian network have been used for direct measurements of apparent velocity (DT/DΔ) and direction of approach of P-waves from 648 seismic events. Our observations are interpreted in terms of vertical anomalies at depths around 350, 1050, 1250, 1700 and 2600 km where the velocity changes very slowly with depth. The corresponding epicentral distances are 35, 47, 53, 62 and 87 deg. In addition, we have strong evidence for existence of lateral P-velocity variation which amounts to around 0.1 kms^{-1} in the depth interval 1750-2300 km and the distance range is around 63-80 deg. A comparison of our data with those presented by others favours lateral velocity variations also at depths around 700-800 km and the corresponding distance range is 25-30 deg.